

High-Power Proton-Linacs

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Snowmass 2001

July 3, 2001

Outline

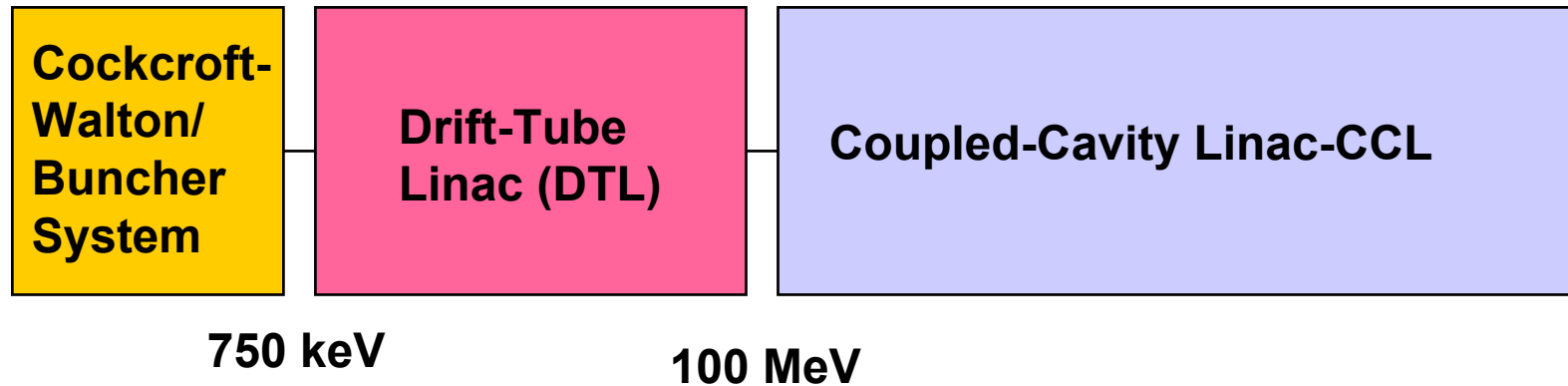
- Introduction to high-power proton linacs
 - Applications
 - Technology progress over past 30 years.
- APT (Accelerator Production of Tritium) as example of a mature design of very high-power linac.
- Halo from beam mismatch.
- Beam halo and beam loss calculations for APT
- Beam Halo Experiment

High Power Proton Linacs

- Many designs within past decade in MW average power range or greater, at ~1 GeV final energy.
- Important applications include material science with spallation neutrons, tritium production, hybrid subcritical reactors for nuclear waste transmutation, and neutrino factories.
- LANSCE linac is the only high-power proton linac that has been built so far. It has operated for almost 30 years.

Linac	Ion	Pulse length (msec)	Rep rate (Hz)	Duty factor	Bunch current (mA)	Average current (mA)	Final energy (GeV)	Ave beam power (MW)
LANSCE	H+	0.625	100	6.25	16	1.0	800	0.8
LANSCE	H-	0.625	20	1.25	9.1	0.1	800	0.08
SNS	H-	1.0	60	6.0%	52	2.0	1.0	2.0
KEK/JAERI	H-	0.5	50	2.5%	50	1.25	0.60	0.75
ESS	H-	1.2	50	6.0%	107	3.85	1.334	5.0
CERN	H-	2.2	75	16.5%	18	1.815	2.2	4.0
CONCERT	H+, (H-)	1.0	50	5.0%	100	5.0	1.334	6.7
APT	H+	∞	--	100%	100	100	1.03	103
ADTF (ATW)	H+	∞	--	100%	13.3	13.3	0.60	8.0

1970's Proton Linac Layout



-Cockcroft-Walton electrostatic generator. Buncher cavities for injection of bunched beam into DTL.

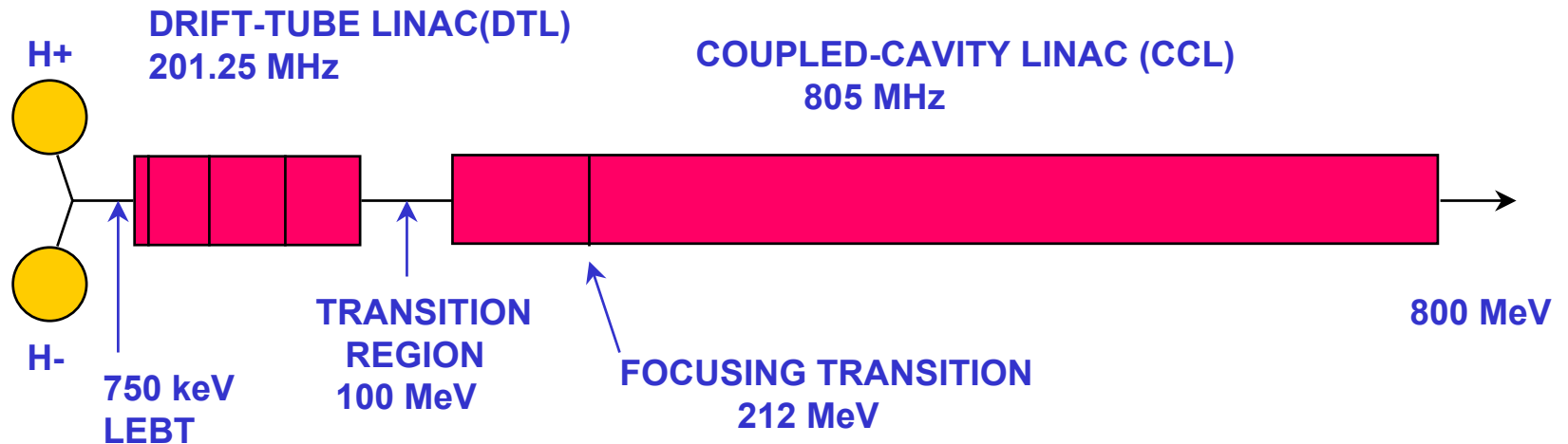
-DTL accelerates beam to about 100 MeV. Uses magnetic quadrupoles in drift tubes for transverse focusing.

-CCL accelerates beam to higher energies. Uses magnetic quadrupoles between multicell tanks for transverse focusing.

-RF field used for longitudinal focusing.

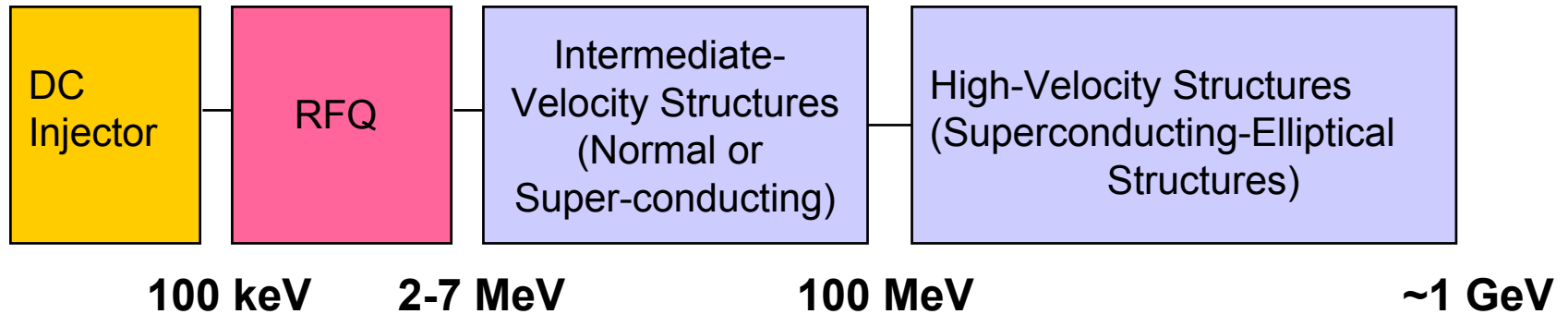
800-MeV LANSCE (formerly LAMPF) Linac

1 mA average current, 0.80 MW for H^+



- First beam: 1972
- LANSCE provides our main experience base for high-power proton linacs.

Modern Proton Linac Layout

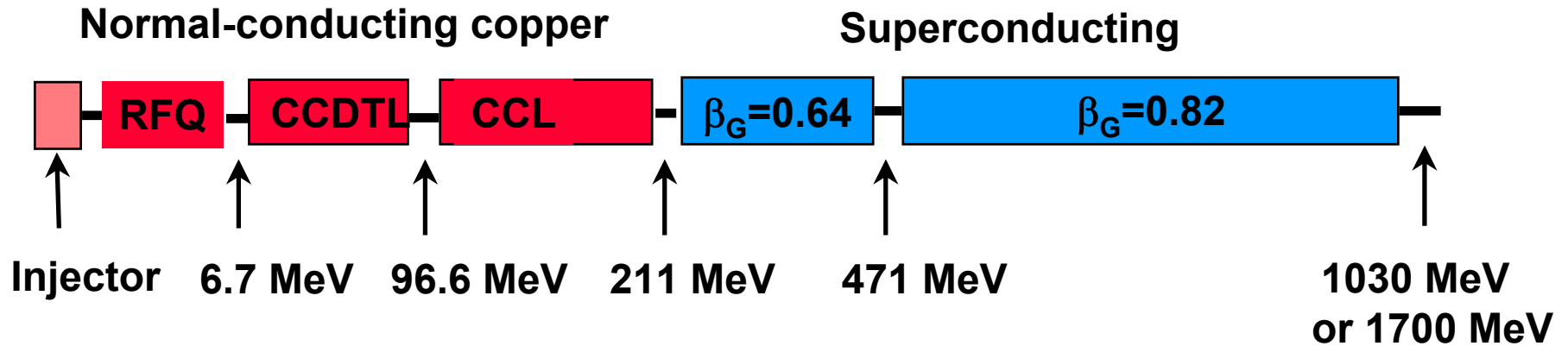


- RFQ bunches and accelerates beam from about 100 keV to a few MeV.
 - Uses RF electric transverse focusing.
 - Larger current limit.
 - Better beam quality
- Intermediate-velocity structures accelerate beam to about 100 MeV.
 - Recent development: superconducting spoke cavities.
- High-velocity structures accelerate beam up to GeV energies.
 - Typically superconducting elliptical cavities are being used.

Accelerator Production of Tritium (APT) project produced proton linac design at 100 MW level.

- **1988:** Tritium-production reactors shut down because of safety concerns. Early CW APT design at LANL for 250 mA, 1.6 GeV.
- **1995:** DOE decision to pursue dual-track strategy to fund design of both reactor- and accelerator-based systems for three year period.
- **1995-1998:** APT design (~100-MW CW proton linac) carried out by LANL, BNL, LLNL, Sandia, TJNAF, Savannah River. Prime Contractor is Burns and Roe, in partnership with GA.
- **1998:** APT is extensively reviewed; reviews conclude APT design is technically sound and will adequately meet nation's tritium needs.
- **1998:** Secretary-of-Energy Richardson announces that commercial light-water reactors will be primary tritium supply technology. APT is the backup technology.
- **Epilog 2000:** Congress authorizes new Advanced Accelerator Application (AAA) program to develop accelerator transmutation of nuclear waste (ATW) technology and provide alternative tritium production technology.
 - A new lower power design for ATW is in progress (ADTF).
 - The 100-MW APT design is an example of a mature high-power linac design.

APT Linac Design



Proton Energy	1030 MeV	or	1700 MeV
Beam Current	100 mA (CW)		
Beam Power (ave)	103 MW	or	170 MW
AC Power for RF	246 MW	or	386 MW
RF Frequency	350/700 MHz		
No. of 1-MW Klystrons	161	or	245
Physical Length	745m	or	1104m

APT Beam-Dynamics Design Objective

- Beam-loss goal above 100 MeV is <0.1 nA/m, comparable to levels throughout most of LANSCE linac.
- This allows essentially uncontrolled hands-on maintenance.
- We have a low beam loss APT design.
 - design avoids known beam-loss mechanisms in LANSCE.**
 - APT has a much larger aperture to rms ratio (13 to 50) than LANSCE (5 to 7).**
 - code simulations predict loss levels much smaller than LANSCE.**
 - additional effects not included in codes have been shown to be unimportant.**

Beam-loss was an important concern at LANSCE because of desire for hand's-on maintenance.

- **Hands-on maintenance is achieved throughout the linac. But several effects were identified as issue for future linacs.**
 - >Longitudinal tails from incomplete beam capture in the 2-cavity bunching system (predates the development of the RFQ).
 - >Poor longitudinal matching and poor acceptance (factor of 4 frequency jump) at 100-MeV transition to CCL.
 - >Dual beam operation (H^+ and H^-) limits effectiveness of beam steering.
 - >LANSCE is pulsed and beam loss is increased during beam turn-on transients.
 - >Small apertures and weak focusing result in small aperture to beam-size ratios.

APT linac design avoided the beam-loss mechanisms in LANSCE.

- APT eliminates longitudinal tails by using an RFQ for bunching.
- Frequency jump reduced to factor of 2 increase and transition moved to low energy; matching capability provided at all transitions.
- Only H^+ is accelerated in APT. Beam steering is much easier.
- Beam turn-on transients eliminated since APT is not pulsed but operates in cw mode.
- Stronger focusing and larger apertures (16-cm diameter in high energy superconducting linac compared with 3.8 cm for LANSCE).

Conclusion of APT Beam Dynamics Studies: Dominant beam-loss issue for APT is the beam halo produced by space-charge forces in a mismatched beam.

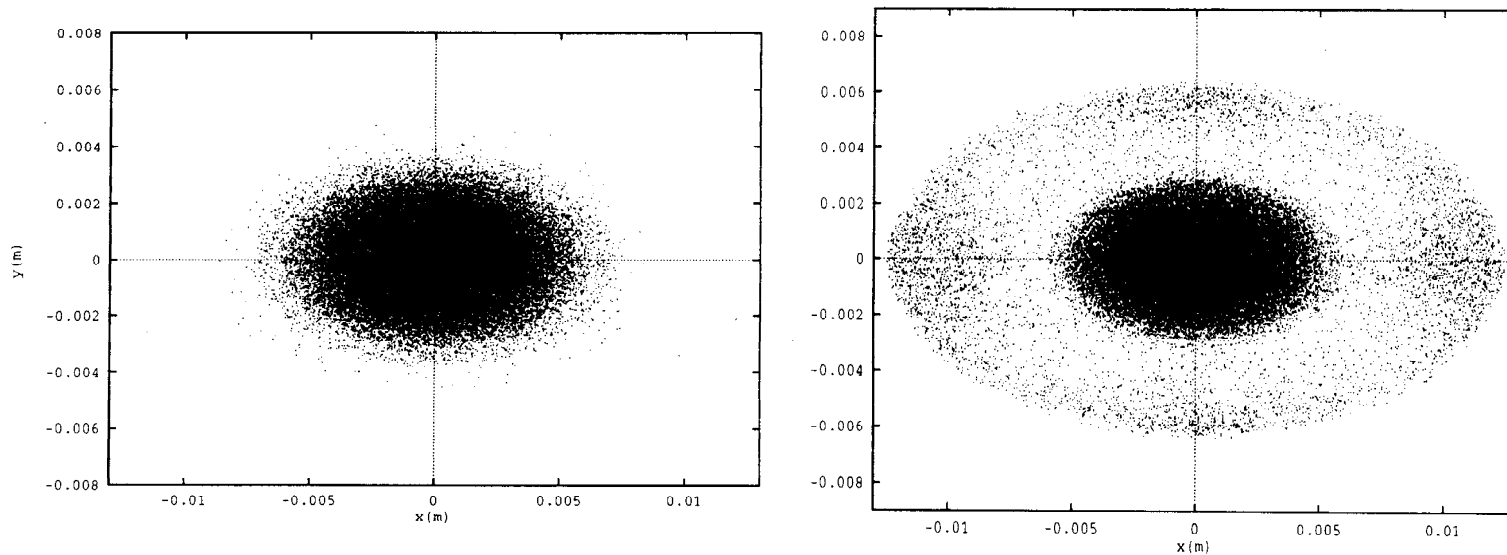
- Beam mismatch induces beam-density oscillations that can resonantly drive some particles to large amplitudes forming halo.
- Analytic particle-core models supported by simulation studies describe physics of the halo caused by mismatch.

Importance of beam matching.

- Beam matching produces a desirable balance between focusing and defocusing forces.
- Beam mismatch produces an imbalance resulting in excitation of rms envelope modes of the beam and **immediate increase in particle amplitudes**.
- During the past decade we learned that individual beam particles executing betatron motion through the oscillating beam core can gain transverse energy from the space-charge force.
- Such particles are **slowly driven to even larger amplitudes** through a space-charge parametric resonance with the core oscillations (identified by R. Gluckstern).
- Analytic particle-core models were constructed for different bunch geometries to describe the resonant behavior of the halo particles.

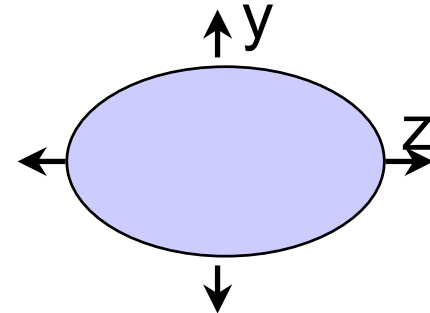
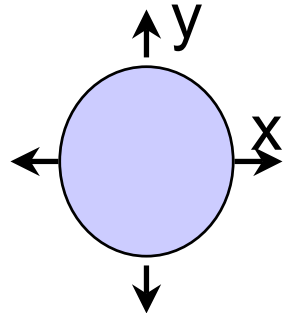
Example of Beam Halo --Simulation of beam transport line with quadrupole focusing shows that halo is formed in mismatched beams.

Rms mismatched beam (on right) develops larger amplitudes than rms matched beam (on left)

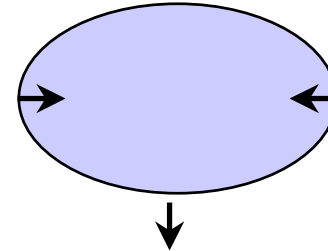
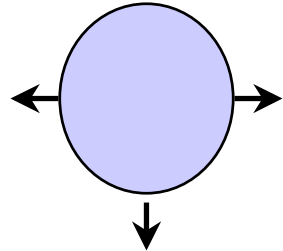


Envelope Modes of Mismatched Bunched Beams

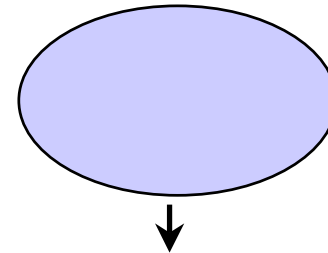
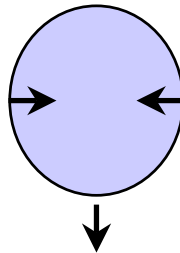
Symmetric
(Breathing)
Mode



Antisymmetric
Mode



Quadrupole
Mode



Details of Particle-Core Model

- Envelope equation models dynamics of the beam core.
- Mismatch the initial core size to excite an “envelope” oscillation mode such as the breathing mode.
- Introduce test particles that experience non-linear space-charge field of oscillating core.
- As particle amplitude increases, particle frequency increases.
- Particles with frequency $f = f_{\text{mode}}/2$ are slowly driven by space-charge of oscillating core to form more extended halo.

Equations for Sphere Particle/Core Model

(Other models include cylinder, and 2D and 3D ellipsoids)

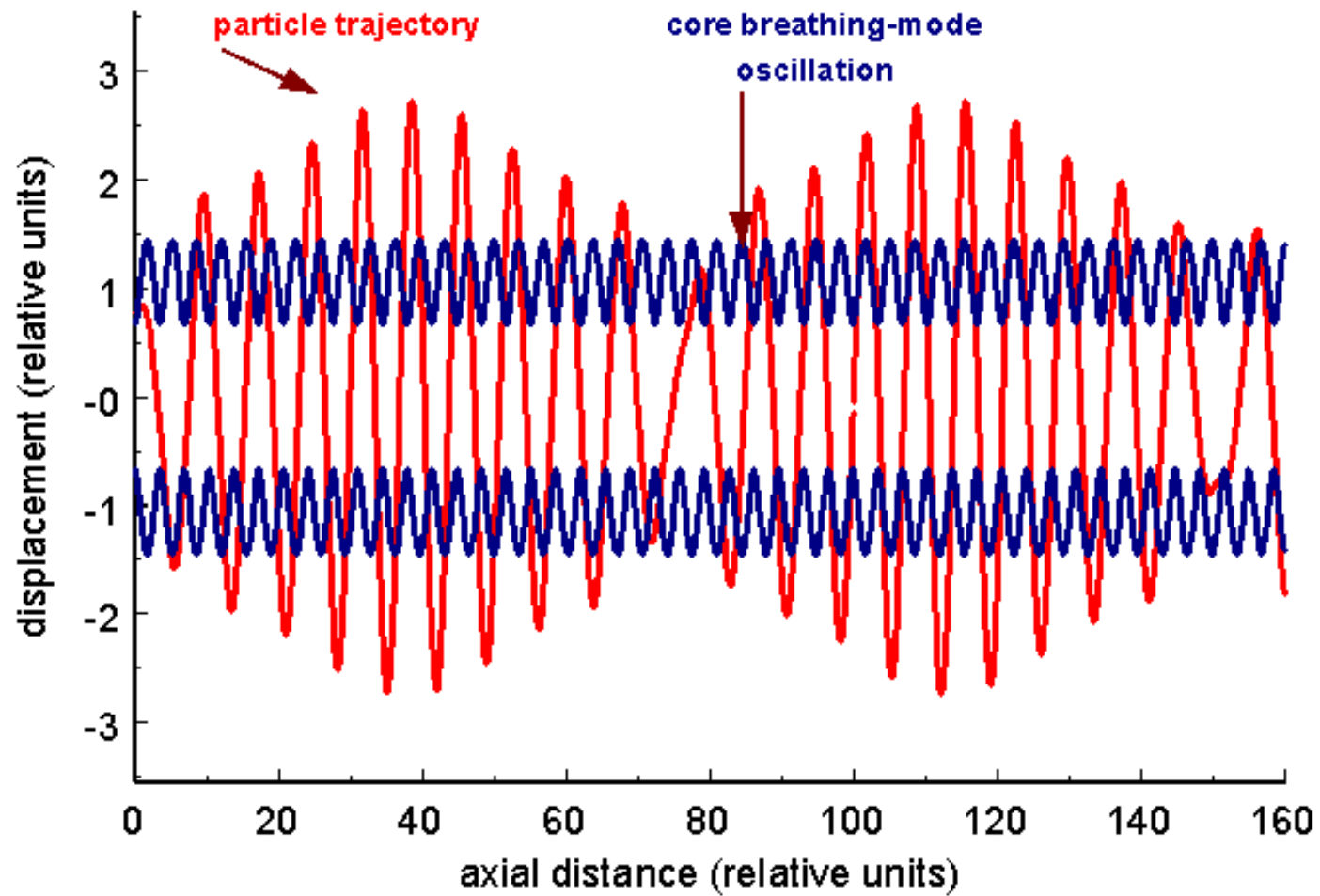
$$R'' + k_0^2 R - \frac{(4\epsilon_{\text{rms}})^2}{R^3} - \frac{\kappa}{R^2} = 0, \text{ envelope equation}$$

$$\text{where } \kappa = \frac{q^2 N}{4\pi\epsilon_0 mc^2 \gamma^3 \beta^2}, \text{ space - charge parameter.}$$

$$x'' + k_0^2 x - \frac{\kappa x}{R^3} = 0, x < R, \text{ particle inside of core}$$

$$x'' + k_0^2 x - \frac{\kappa |x|}{x^3} = 0, x > R, \text{ particle outside of core.}$$

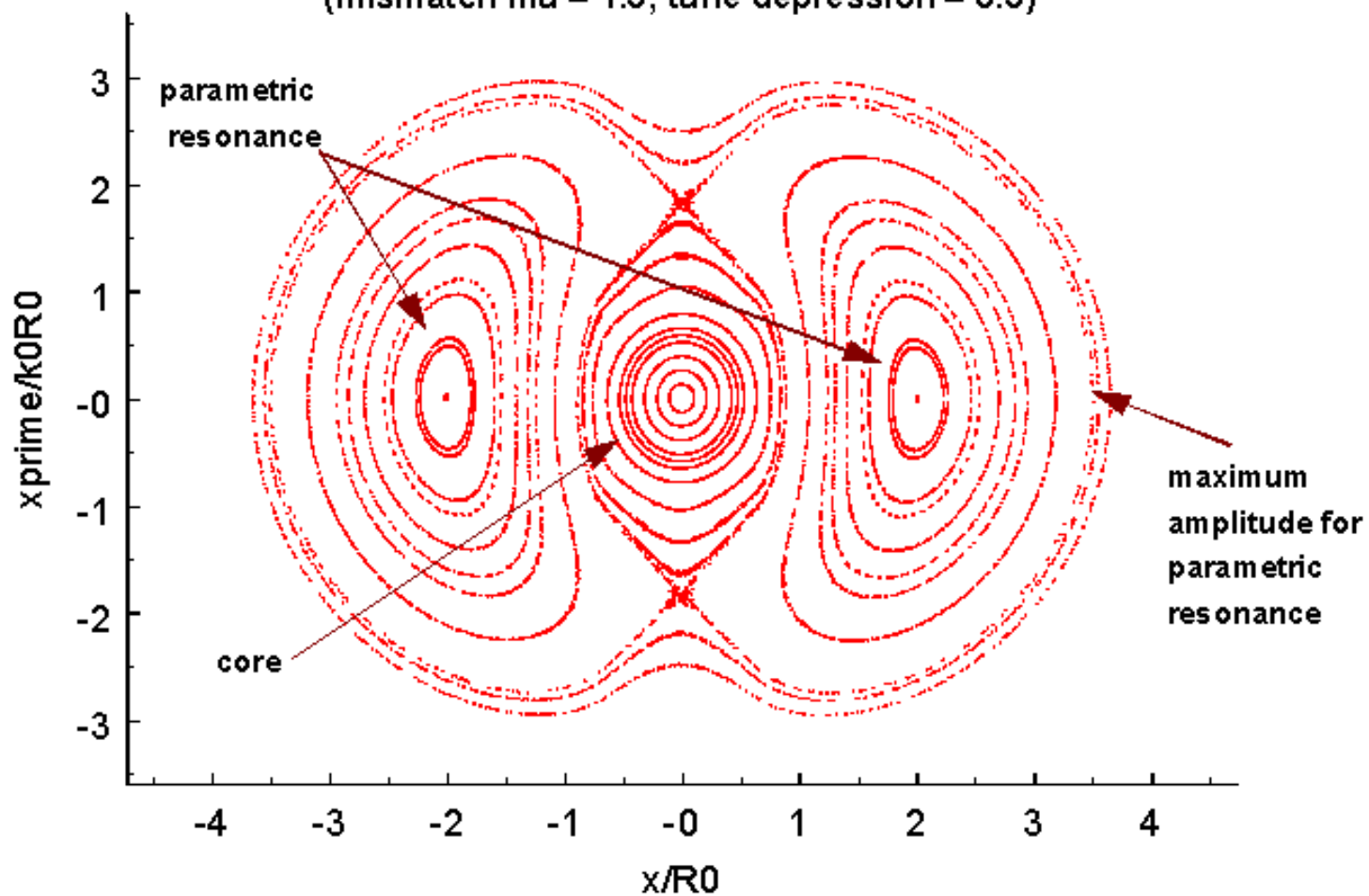
Parametric Resonance in Sphere Particle-Core Model



Stroboscopic Phase Space Plot

Particle-Core Model - Spherical Bunch - Breathing Mode

(mismatch $\mu = 1.5$, tune depression = 0.5)

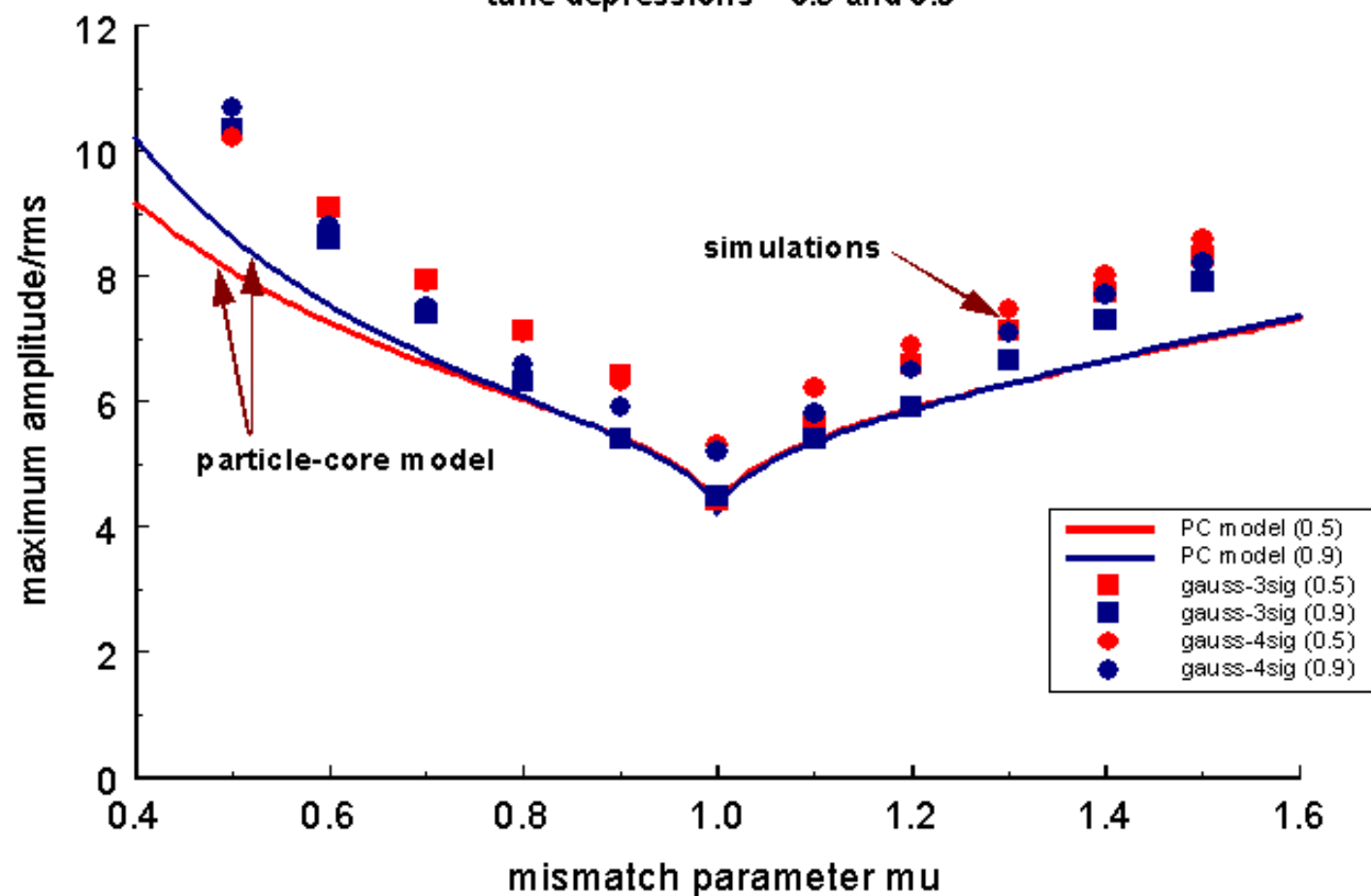


Particle-core model summary

- Halo extent is limited because of the amplitude-dependence of particle-oscillation frequency (simulations confirm this as a good approximation).
- Growth rate of halo increases as beam becomes more space-charge dominated).
- Ellipsoidal models (Maryland, LLNL, and LANL) show bunch aspect ratio dependence. For $z > 2r$ symmetric (breathing) mode generates mostly transverse halo. Antisymmetric mode generates mostly longitudinal halo.
- Rf nonlinear force disrupts the parametric resonance condition for longitudinal halo. (*J. Barnard and S. Lund*). Simulations confirm that longitudinal halo is well confined within rf bucket.
- Scaling formula shows that to limit the halo you want strong focusing, good matching, and high frequency.

Simulations of Spherical Gaussian Bunch Compared with Sphere Particle-Core Model

tune depressions = 0.5 and 0.9



Results of the particle-core models are supported by multiparticle simulations.

- Halo extent is limited because the large amplitude particles fall out of resonance (amplitude-dependence of particle-oscillation frequency).
- The prediction of a maximum halo extent for a given mismatch is confirmed by simulations.
- Nonlinear rf longitudinal focusing reduces longitudinal particle frequencies and reduces extent of the longitudinal halo.
 - APT longitudinal halo is confined within the rf bucket even for very large mismatches.

Scaling of maximum resonant amplitude from sphere particle-core model suggests design guidelines.

$$x_{\max} \cong 5 \sqrt{\frac{\varepsilon_n}{k_0 \beta \gamma}} [1 + u]^{2/3} [1 + |\ln(\mu)|],$$

where

$$u = \frac{q^2 N}{20 \sqrt{5} \pi \varepsilon_0 m c^2 (k_0 \beta \gamma^3 \varepsilon_{n,\text{rms}}^3)^{1/2}}.$$

μ = match parameter

β, γ = velocity, relativistic mass factor

N = particles per bunch

$\varepsilon_{n,\text{rms}}$ = rms normalized emit tance

k_0 = zero – current transverse wave number

Design Guidelines From Particle-Core Model for Minimizing Resonant Halo Amplitude

- Good matching is important but one cannot assume that matching can be good enough to avoid halo.
- Small rms emittance reduces halo amplitude.
- Small number of particles/bunch N avoids severe tune depression. (*Want high bunch frequency for given average current.*)
- Strong linear focusing.
- But nonlinear focusing that weakens with increasing amplitude can disrupt the parametric resonance.
- These effects are less important at high energy.

Linac Errors and Beam Halo

- Halo is caused by linac errors that lead to mismatch.
- LINAC code uses Monte Carlo approach to choose machine parameters within known tolerances.
- Results of LINAC-code error studies:
Starting with a realistic beam from the ion source and neglecting LEBT and RFQ imperfections, no linac particle loss was observed for total of 3M particles (30 runs with 100,000 particles per run) in simulations with random linac errors included.

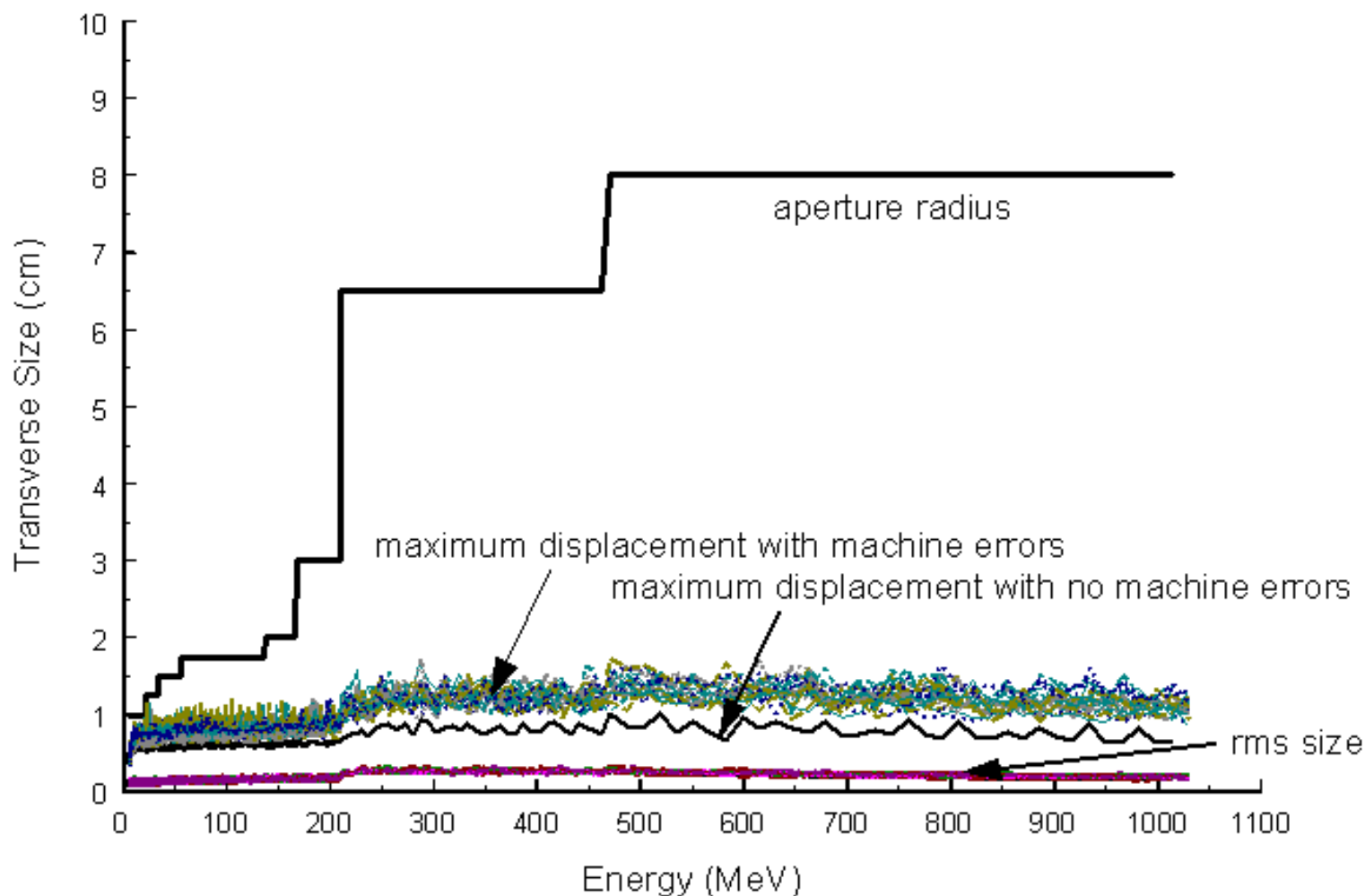
LINAC Space-Charge Calculations

- The simulation programs use the particle-in-cell (PIC) method, effectively solving the Vlasov-Poisson equations numerically.
- Programs compute the space-charge field at each time step and apply it together with the focusing fields to advance the particles.
- Different space-charge routines, SCHEFF (2D r - z with corrections for 3D effects) and 3D PIC (full 3D space-charge calculation) agree very well with each other. SCHEFF also agreed with rms beam measurements at LANSCE.

Multiparticle simulations for the APT beam line show that beam loss is low.

- Made 20 runs with 100,000 particles and different sets of random errors for each run (2-million particles total).
- Zero particle loss is observed above 20 MeV. Loss of a single particle above 100 MeV would correspond to a loss rate of 0.05 nA/m, lower than the APT design goal.
- 5 particles total were lost after the RFQ, all with energies below 20 MeV. This loss rate corresponds to very small activation level <1mRem/hr.
- As another check, several 10^7 particle runs were made on the parallel computers with full set of errors in the linac after the RFQ. These runs produced no particle loss after RFQ.

2 Million Particles through Linac to Target with Full Set of Machine Errors
20 runs with different random errors -- 100,000 particles per run



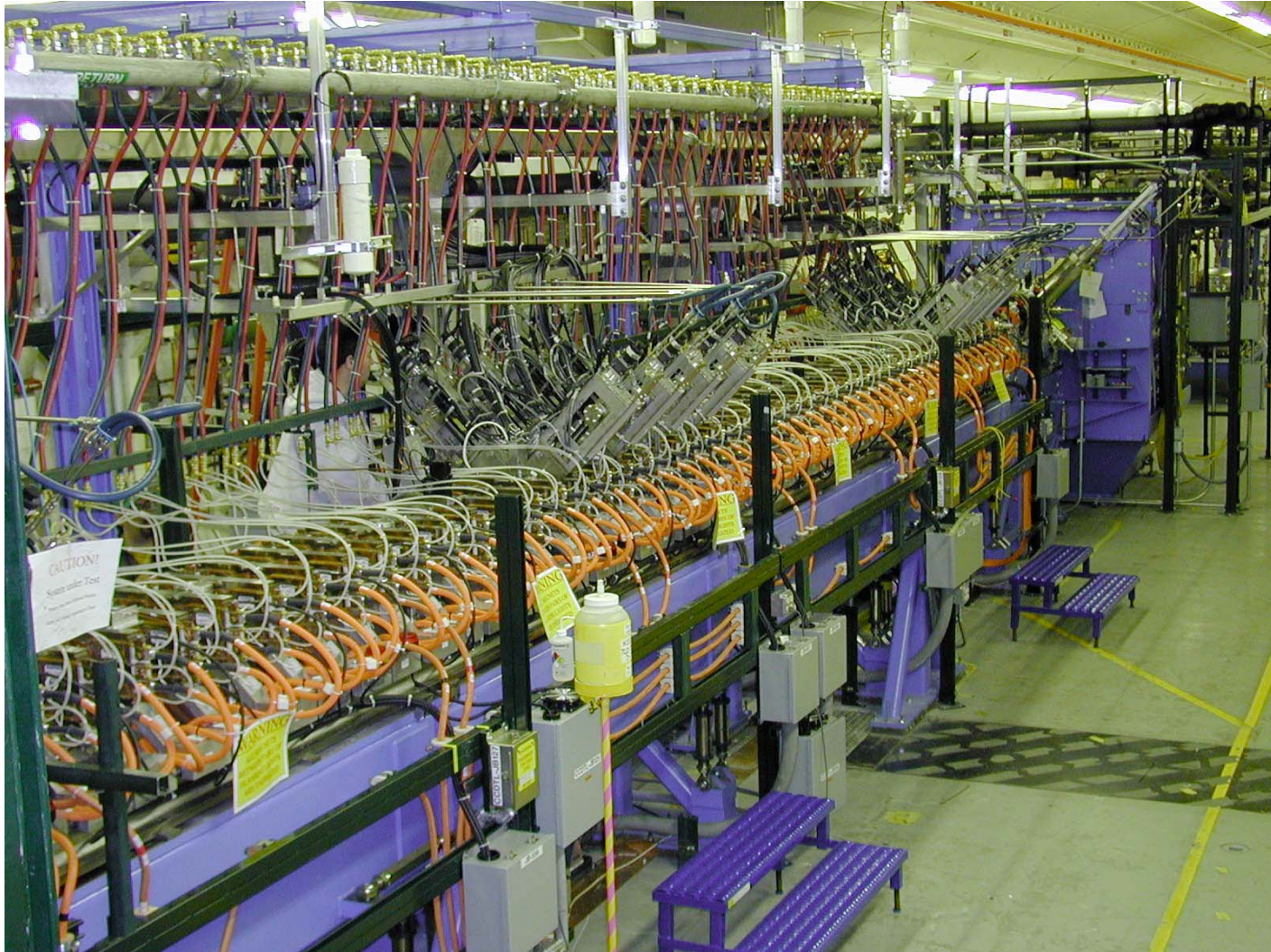
Summary and Conclusion about APT low beam loss design

- Achieving a low beam-loss APT design is based on four steps.
 - 1) Understanding the performance of the LANSCE linac using measurements and simulation.
 - 2) Development of a theoretical understanding of the halo-formation mechanism in APT.
 - 3) Design of APT to avoid the beam-loss mechanisms.
 - 4) Using detailed multiparticle simulations of APT to predict the expected beam loss.

Beam-Halo Experiment

- 75-mA pulsed beam ($\sim 30\text{-}\mu\text{sec}$ pulse, 1-Hz) from 6.7-MeV RFQ at LEDA facility.
- FODO transport line with 52 quadrupoles and ample complement of beam diagnostics.
- First four quadrupoles are used to create breathing- and quadrupole-mode mismatches.
- 10 mismatch oscillations, enough to produce measurable halo growth as predicted by simulations.
- Use special beam-profile scanners consisting of a thin wire for core measurement and plates for halo measurement. Large dynamic intensity range for beam profile (at least 10000).
- Vary mismatch and current. Measure and compare with codes 1) **rms emittances**, 2) **maximum detectable amplitudes**, 3) **kurtosis** (beam profile parameter).
- Also search for additional halo from other sources.

LEDA Facility Halo Lattice



Halo Experiment Scientific Team

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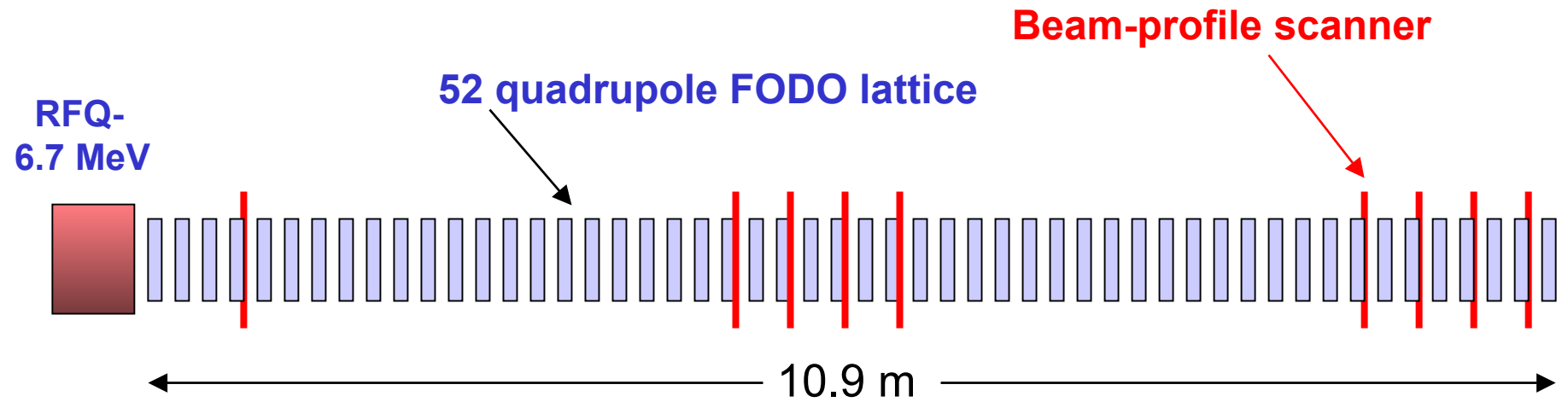
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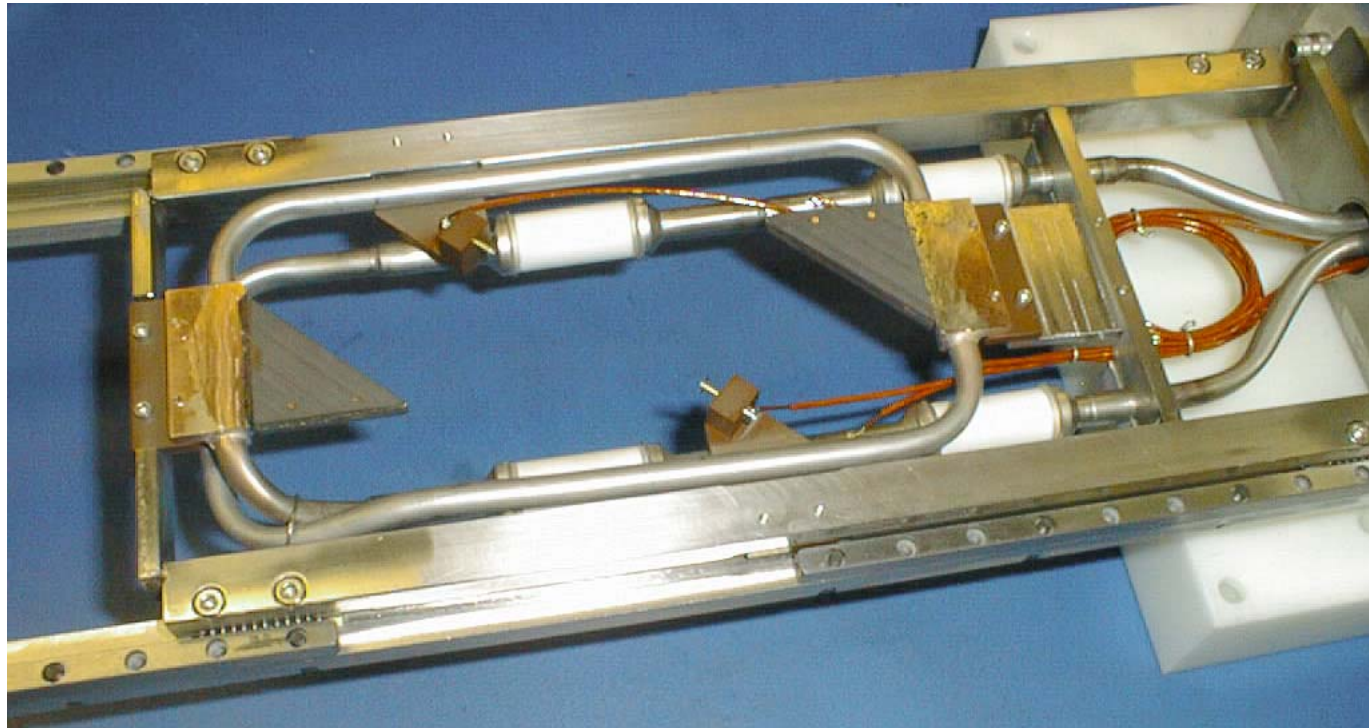
Beam-halo experiment



Beam profile monitor is our main halo diagnostic tool (J.D.Gilpatrick, et al.)

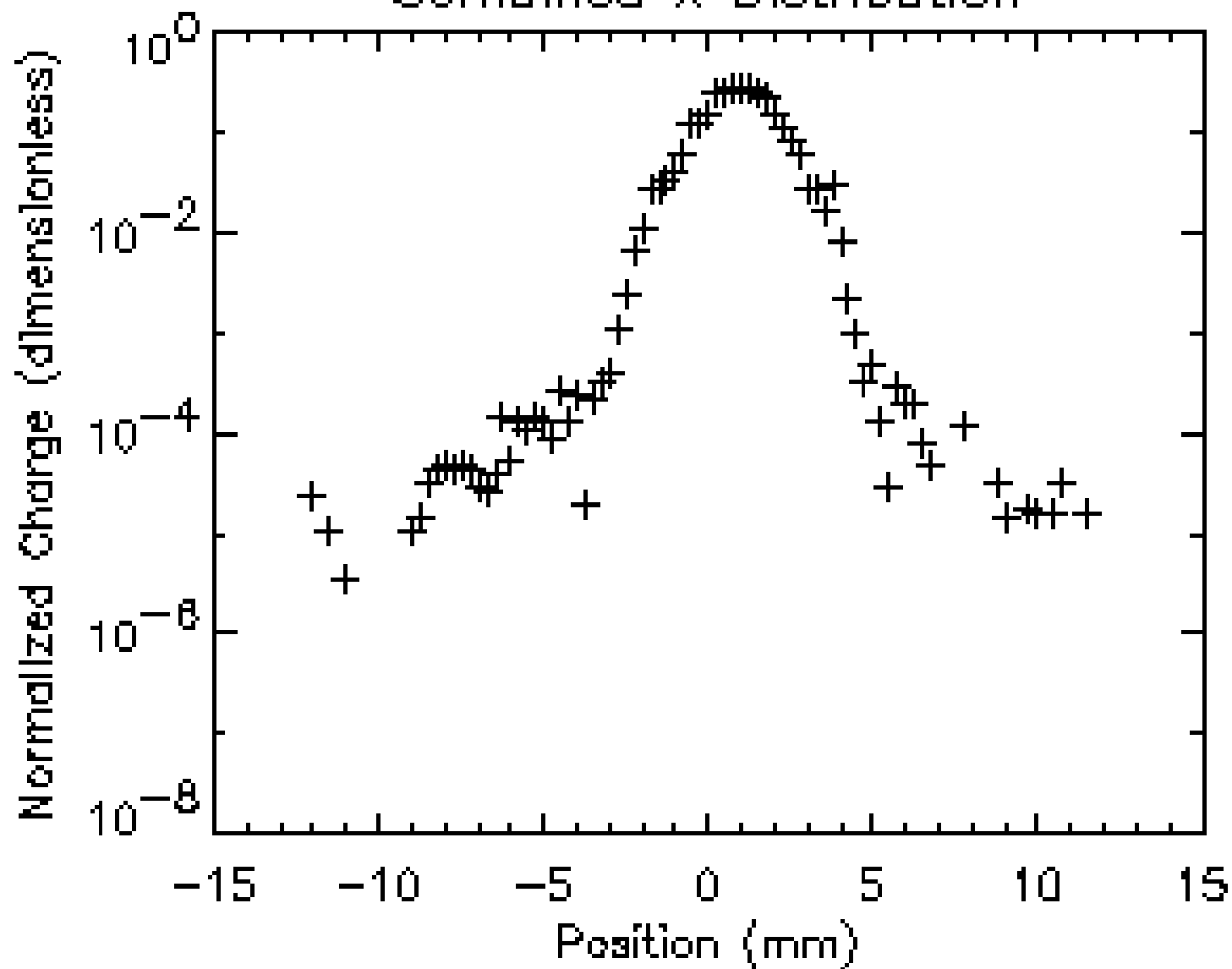
- 9 measurement stations at which both horizontal and vertical projected distributions are measured.
- Wire is 33μ carbon fiber to measure core.
 - Stopping range of protons is 300μ so protons pass through wire.
 - Wire signal is due to secondary electron emission.
 - Wire bias voltage about -10V to enhance signal.
- Scraper is graphite plate brazed onto copper. Scraper measures halo
 - Graphite is 1.5 mm thick so protons stop in graphite.
 - Scraper bias voltage about +10V to suppress secondary electron emission.
 - Copper is water cooled.
- Simulations predicted dynamic range of $10^3:1$ for wire alone and $10^5:1$ for wire plus scraper. Approximately confirmed by observations.
- Simulations predicted wire can detect to 4 rms. Halo scraper extends this to 5 rms.

Close-Up of the Movable Frame of the Halo WS/HS Assembly

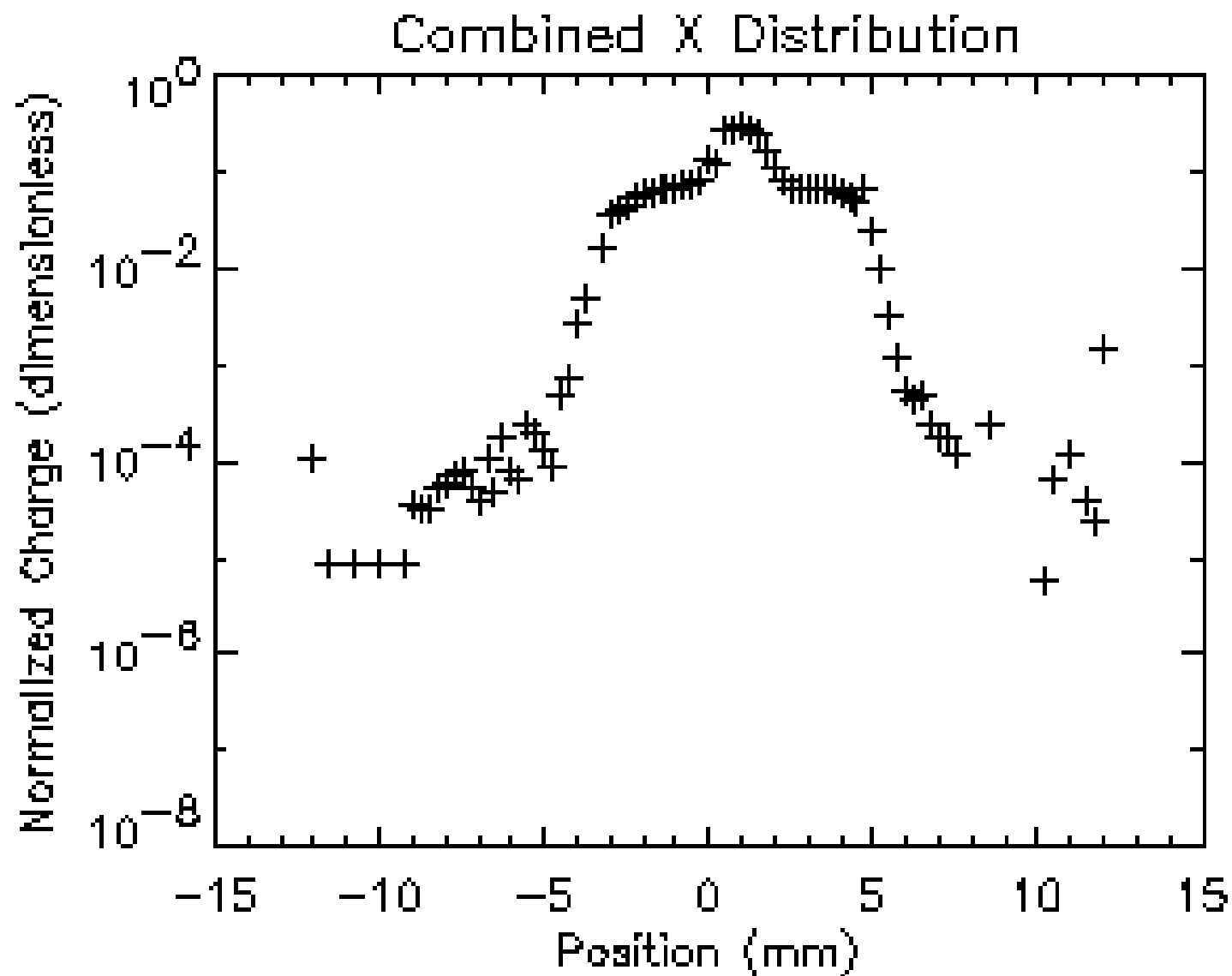


Matched beam - 75 mA - scanner 51x

Combined X Distribution



Mismatched beam ($\mu=1.5$)-75 mA-scanner 51x



Status of halo experiment

- Measurements at 75 mA show rms emittance growth that increases with increasing beam mismatch as qualitatively; growth rate is higher than expected from initial simulations.
- Measurements at 16 mA show no emittance growth as expected from simulations.
- The shapes of the transverse beam profile distributions are not yet understood.
- Analysis and additional measurements are in progress